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Analysis of Rainfall Variables Trends and Potential Vegetation Responses in Sinaloa, México

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Abstract

Based on monthly data from 55 meteorological stations from the North Pacific Watershed, seven annual rainfall trends were estimated and analyzed using non-parametric tests. The estimated slopes were analyzed in a geographic context to determine a potential spatial arrangement. Finally a brief analysis of the potential vegetation response from the different physiographic regions and the implications in the productive analysis is discussed. The findings indicated divergent trends in all the proposed variables, in general increasing and drier trends were found. Latitude was the most relevant factor regarding trend behavior in geographic terms. The lack of awareness and apathy from the authorities in the region were found, plus the regional vulnerability may originate notorious and serious consequences if the proper measures are not taken into account.

Keywords

Climate Change, Rainfall Trends, Vegetation Responses

1. Introduction

Within the context of climate change, it has been implied that one of the most evident consequences is the modification of the water cycle [1] [2], essentially affecting the precipitation patterns [3] [4]. Rainfall increasing irregularities have been documented from global [5]-[7] to regional scales [8]-[10]. These irregularities also have divergent trends [11]-[13]. Although the process of climate change has modified rainfall patterns worldwide, the changes are not equal, localized sites within a watershed may develop different attributes of change in relation to

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intensity and direction [14] [15], e.g. drying or increasing rainfall trends; or its temporal variability, *i.e*. seasonality. Particularly for México, [16]-[18] reported opposing results at different time scales in a regionalized analysis.

Rainfall is of paramount importance for biological responses and distribution of almost all terrestrial living organisms. Vegetation is crucial in almost all ecosystems, since it is the first link of the trophic chain. Rainfall is a key element that determines relevant parameters of the vegetation such as its distribution [19], diversity [20], functionality [21] and structure [22]. The interaction between climate factors and vegetation is crucial for ecosystem health, since plants develop and maintain feedback processes with the environmental factors that drive the ecosystem processes and hence its stability [23]. On seasonal arid and semiarid ecosystems, water availability is extremely important for plant adaptations and hence its responses [21] [24].

The biological responses due to climate change have been widely documented [25] [26], particularly for plants, from physiological function [27]-[29], to geographic distribution changes [30] [31] and ultimately to adaptive responses [32] [33]. In arid zones, rainfall contributes to establishing ecosystem productivity rates [34]. Precipitation patterns also constitute an important factor that affects water availability as a resource [35]. Updating rainfall trends generates essential information for productive activities as agriculture, power generation and ultimately food production security, therefore, regional variability in rainfall patterns must be analyzed in depth [13].

For Sinaloa at this point, there is not a study that illustrates the behavior of rainfall variables within the frame of climate change. This analysis can place a basis not only for Sinaloa, but inside a regional context of northwest México, given that the main factors that drive the climate machinery of Sinaloa also affect a great portion of the cited region. The importance of this analysis not only relies on the ecosystem processes, but also on productive activities such as agriculture, fisheries and cattle production, which are the main economic activities of Sinaloa. The purpose of this work is to examine the rainfall trends and its associated variables, its relationship with their geographic location and to briefly explore the potential effects on its main vegetation types and agriculture activities consequences.

2. Methods and Materials

2.1. Study Area

Sinaloa is a Mexican province located at the northwest Pacific coast of Mexico. Its long-narrow shape, that makes latitudinal change more prominent than longitudinal, is bounded in the west by the Sea of Cortés and by the Sierra Madre Occidental in the east (**Figure 1(a)**). There is an increasing width of the coastal plains towards the northern edge of the state. As a result of those factors among others, following the climate categorization by [36], its climate classification range from temperate sub-humid with summer rains to very warm and dry, the difference between them are mainly established by the length of the summer-rainfall season and the differences in extreme temperatures.

Rainfall patterns in the Sea of Cortés eastern coasts, increase in seasonality as one moves to the north, this pattern is mainly determined by a monsoon regime [37]-[39], which is driven mainly by the position of the Intertropical Convergence Zone [40] and are also influenced by the El Niño Southern Oscillation phenomenon [41] [42]. Summer rainfall from May to October represent the main portion of the total annual amount; early summer rainfall events are frequently the result of convective storms, late summer rains are often associated with tropical storms [43] [44]. The winter rainfall fraction tends to be more important in the northern region of Sinaloa. The orography of this region is a crucial factor in the rainfall pattern; the altitude and shape of the mountains determine a lot of aspects of these processes [45] [46].

2.2. Physiographic Regions

In Sinaloa, three major physiographic regions can be clearly identified: the Coastal Plains, the Sierra Foothills and the Sierra Madre [36]. These strip shaped regions lie parallel to each other and to the coast (**Figure 1(b)**). A main factor that determines the differentiation between physiographic regions is the orography. The Coastal Plains (CP) are essentially flat areas that range from the sea level to 150 meters above sea level (masl), with few and scattered low hills. This region covers 46% of the entire area of the state of Sinaloa. This area contain essentially thorn forest vegetation [47] which in the northern edge include some vegetation elements of the Sonoran

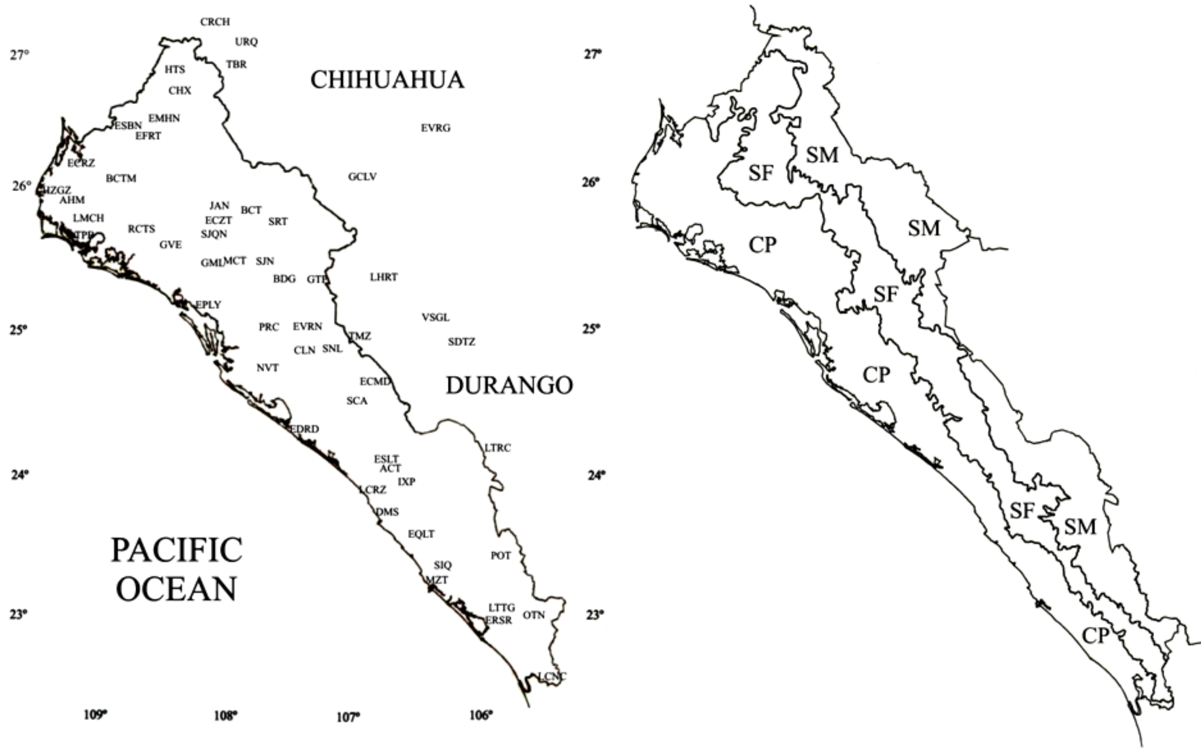

Figure 1. (Left) Sites of selected weather stations of the North Pacific Watershed, see **Table 1** for abbreviations; (Right) CP = Coastal Plains; SF = Sierra Foothills; SM = Sierra Madre.

Desert [48], a few of these elements can be found southward until 26˚N. In the Sierra Foothills (SF), the orography consists in hills from 150 to 900 m, with increasing steepness and altitude towards the east. This area encompasses 14% of the territory. The most common type of vegetation within this region is the tropical dry forest [47]; other types include riparian forest along creeks and rivers that flow westward and the sub-deciduous forests mainly in the eastern higher boundaries of this region. The Sierra Madre (SM) which covers the remaining 40% of the Sinaloa area, can contain tropical dry and sub-deciduous forest, but above 1000 masl, other types of vegetation associated with more mesic conditions such as the oak forest, oak-pine forest begin to be more conspicuous, pine forest dominates above 1200 masl.

A consideration must be taken regarding the position of some stations used for this analysis, the altitude of certain stations do not match the position within a particular physiographic region, this is due to its geographic location, as an example, Culiacán and Mocorito among others sites are placed within the SF region and their respective altitudes are below 100 masl, but these sites are spatially surrounded by hills and inside the cited region.

2.3. Potential Vegetation Responses

Potential modification of the structure and composition of the vegetation and its association to climate change is discussed by [49] [50] by modeling mechanisms or directly through field evidence [51] [52]. In general at large spatial and temporal scales, the processes that determine the causes of rainfall patterns and its seasonality are multifactorial and complex, however, at a regional extent, physical evidence of anthropogenic activities that influence the decline of rainfall amount have been explained, mainly through thermodynamic mechanisms. The potential causes include change of soil cover by deforestation for agricultural purposes [53] or logging [54]. The effects of anthropogenic change of soil cover are faster and more evident than the potential response of vegetation [55]. The results of these effects can go from local to regional scale [56] or quasi-continental magnitude [57].

In southern México, [16] [17] described rainfall trends alterations linked to deforestation. [58], using modeling programs described the potential modification of vegetation cover, specifically for Sinaloa, that covers a great portion of the North Pacific Watershed, they predict a great reduction for the template forest, which would be replaced by tropical dry forest, an extension of thorn forest towards the south of the area and the replacement of sub-deciduous and template forest by tropical dry forest in an altitudinal direction. Cloud forest would get into the brink of extinction and the pressure of the riparian vegetation would multiply in a already decimated riverine vegetation.

2.4. Climate Data

The monthly data of 55 weather stations was provided by the Comisión Nacional del Agua (CNA) (**Table 1**). Stations were chosen on the basis of data availability and completeness. The selected stations are placed in the state of Sinaloa, western Durango and southwest Chihuahua, within the North Pacific Watershed, in the western windward slopes of the Sierra Madre Occidental. The chosen stations are placed in sites where, rivers and their main tributaries originate and flow westward through Sinaloa into the Pacific Ocean. Seven variables associated to rainfall were estimated. For the purpose of this analysis, the start of an annual rainfall year was considered in the winter at the start of the dry season in November. Annual rainfall values (PP) were formed by adding monthly totals. The degree of rainfall seasonality was estimated using the Precipitation Concentration Index (PCI) proposed by [59]. Summer rainfall (PPS) was calculated by adding monthly values from May to October. Winter rainfall (WPP) was calculated summing the monthly totals from November to April. The percentage of winter rainfall (%WPP) was calculated by dividing WPP between the PP. To estimate the length of the dry season, between October and May, we counted the number of months with total rainfall below 15 mm (PP < 15) and the longest streak of consecutive months with rainfall below 100 mm (DS).

2.5. Statistical Analysis

To determine the existence of a trend of the rainfall variables proposed and to measure the magnitude of the change in each station, the Mann-Kendall test and Sen's slope calculations were performed on each annual time series. The Mann-Kendall test is a non-parametric test that does not requires a normally distributed set of data. A thoroughly description of this method is detailed in [60] [61].

To describe the behavior of the rainfall variables slopes in geographic terms, two analyses were performed: 1) a multiple linear regression analysis, using the slope values as dependent variables and latitude and altitude as independent variables, in order to estimate the β-standardized values; and 2) a spatial correlation analysis estimating the Moran's I Index. Finally, a principal component analysis (PCA) is performed in order to elucidate the most relevant aspects regarding the variability of rainfall processes in this region.

3. Results and Discussion

3.1. Annual Trends

Opposing trends were detected for all the rainfall analyzed variables. 37 stations displayed PP negative drying trends, eight were significant. Only three stations presented increasing significant rends (MZT, TPB and URQ). Divergent trends have been already characterized at a more extended spatial scale by [62]-[64] among others. Increasing PCI trends were also found in 37 stations, ten were significant, only BCTM showed a significant decreasing trend for PCI. SDTZ in the state of Durango was the only station with a negative trend below 25˚N. A similar scenario with opposing trends for PCI was found in Spain by [65] and in India by [66].

Four potential scenarios can be drawn from the interaction between PP and PCI. A first situation with decreasing PP and increasing PCI trends is the most frequent in this region, this combination hints a less amount of annual rainfall distributed in a more irregular fashion throughout the year, probably stretching the drought length. This situation is found in 28 stations, scattered mainly from the mid to southern and eastern regions of the analyzed area. Eight stations were found with decreasing PP and decreasing PCI trends. This combination can suggest a drought-prone situation, due to a less amount of rainfall more evenly dispersed in temporal terms, worsening things in an already seasonally dry environment. Given the markedly seasonal nature of the rainfall in this region, an increasing PP and increasing PCI trend combination could pose an even more extreme situation with an equally or higher amount of rainfall in a less number of rainfall events, in some studies decreasing rainfall trends have been associated with the increase in intensity of rainfall events [67]-[69], this can generate

Table 1. Sites, physiographic region, latitude, longitude and altitude of the analyzed weather stations in Sinaloa. SF = Sierra Foothills, CP = Coastal Plains, SM = Sierra Madre.

Site	Abbreviation	Years of Data	Region	Latitude N	Longitude W	Altitude (m)
Acatitán	ACT	1962-2012	SF	24˚05'	−106˚40'	132
Ahome	AHM	1962-2007	CP	25˚55'	−109˚10'	10
Bacurato	BCT	1980-2009	SF	25˚51'	−107˚52'	234
Boca Toma	BCTM	1962-2007	CP	26˚04'	−108˚46'	36
Badiraguato	BDG	1962-2012	SF	25˚20'	−107˚32'	235
Cerocahui	CRCH	1959-2006	SM	27˚18'	−108˚03'	1500
Choix	CHX	1962-2012	SF	26˚44'	−108˚20'	234
Culiacán	CLN	1956-2012	CP	24˚47'	−107˚25'	60
Dimas	DMS	1963-2012	CP	23˚43'	−106˚47'	19
El Carrizo	ECRZ	1966-2007	CP	26˚16'	−109˚03'	20
El Cazanate	ECZT	1967-2006	SF	25˚49'	−108˚01'	930
El Comedero	CMD	1981-2012	SF	24˚37'	−106˚49'	238
El Dorado	EDRD	1970-2010	CP	24˚19'	107˚21'	11
El Fuerte	EFRT	1959-2010	SF	26˚25'	−108˚37'	84
El Mahone	EMHN	1962-2005	SF	26˚30'	−108˚35'	135
El Playón	EPLY	1962-2012	CP	25˚13'	−108˚12'	5
El Quelite	EQLT	1980-2012	CP	23˚33'	−106˚28'	40
El Rosario	ERSR	1964-2012	CP	22˚59'	−105˚51'	32
El Sabino	ESBN	1966-2005	SF	26˚29'	−108˚44'	123
El Salto	ESLT	1997-2012	SF	24˚07'	−106˚41'	160
El Varejonal	EVRN	1962-2012	SF	25˚06'	−107˚23'	177
El Vergel	EVRG	1975-2006	SM	26˚28'	−106˚23'	2740
Guadalupe y Calvo	GCLV	1959-2006	SM	26˚06'	−106˚58'	2316
Guamúchil	GML	1953-2012	CP	25˚28'	−108˚05'	50
Guasave	GVE	1974-2012	CP	25˚33'	−108˚28'	36
Guaténipa	GTP	1965-2012	SF	25˚20'	−107˚13'	350
Higuera Zaragoza	HZGZ	1962-2006	CP	25˚58'	−109˚18'	9
Huites	HTS	1962-2006	SF	26˚53'	−108˚21'	214
Ixpalino	IXP	1965-2012	SF	23˚58'	−106˚36'	65
Jaina	JAN	1962-2012	SF	25˚53'	−108˚01'	194
La Concha	LCNC	1961-2012	CP	22˚32'	−105˚27'	21
La Cruz	LCRZ	1993-2012	CP	23˚55'	−106˚53'	30
La Huerta	LHRT	1969-2012	SM	25˚21'	−106˚42'	670
Las Tortugas	LTTG	1974-2012	SF	23˚05'	−105˚50'	131
Las Truchas	LTRC	1962-2012	SM	24˚10'	−105˚58'	1794

Continued

Los Mochis	LMCH	1957-2010	CP	25˚48'	−109˚00'	14
Mazatlán	MZT	1971-2012	CP	23˚12'	−106˚25'	5
Mocorito	MCT	1965-2012	SF	25˚29'	−107˚55'	85
Navolato	NVT	1968-2012	CP	24˚45'	−107˚43'	14
Otatitán	OTN	1982-2012	SF	23˚00'	−105˚40'	148
Pericos	PRC	1962-2009	CP	25˚05'	−107˚41'	54
Potrerillos	POT	1969-2012	SF	23˚27'	−105˚49'	1470
Ruiz Cortines	RCTS	1964-2006	CP	25˚42'	−108˚43'	20
San Diego Tenzaens	SDTZ	1973-2012	SM	24˚52'	−106˚07'	1489
San Joaquín	SJQN	1978-2012	SF	25˚40'	−108˚02'	140
San Juan	SJN	1990-2012	SF	25˚29'	−107˚50'	112
Sanalona	SNL	1962-2012	SF	24˚48'	−107˚09'	137
Santa Cruz Alayá	SCA	1962-2012	SF	24˚29'	−106˚57'	120
Siqueros	SIQ	1966-2012	SF	23˚25'	−106˚23'	55
Surutato	SRT	1961-2012	SM	25˚48'	107˚34'	1400
Tamazula	TMZ	1959-2012	SM	24˚56'	−106˚58'	254
Topolobampo	TPB	1963-2008	CP	25˚36'	−109˚03'	34
Tubares	TBR	1974-2005	SM	26˚56'	−107˚58'	321
Urique	URQ	1968-2008	SM	27˚10'	−107˚55'	599
Vasco Gil	VSGL	1967-2012	SM	25˚08'	−106˚21'	2417

flashfloods and severe erosive events, specially on sites with steep slopes. Finally, the mixture of increasing PP and decreasing PCI occurred only in stations above 25˚N in CHX, ECRZ, ECZT, EVRG, GCLV, GML, LCHM, TBR and URQ. This condition can suppose a less severe situation where a larger amount of annual rainfall is more evenly distributed along the year. The interaction of PP and PCI trends is shown in **Figure 2**.

The amount of PPS is the most important fraction of the year, not only in terms of quantity but also as the main driving element for ecosystem processes. 31 stations developed negative drying trends, but only EPLY, GVE and ESBN were significant. On the other hand, LTRC, NVT, TPB and URQ presented significant increasing trends (**Figure 3**).

Although in terms of quantity PPW is not strictly important, its amount can reflect the condition of ecosystem processes. If winter precipitation is considerable, it can diminish the effects of the drought length. Nevertheless, the winter rainfall regionally known as *Equipatas* are no longer as frequent as they used to be, mainly in the mid and southern areas within the analyzed watershed, only14 stations developed increasing trends, none of them was significant and all were located above 25˚N (**Figure 4**). The %PPW trend analysis showed a similar pattern (**Figure 5**). The length of the dry season was measured through PP < 15 and DS. For the first case 49 stations showed an increase in the number of months with monthly rainfall below 15 mm, the increasing sites PRC, GCLV, EVRG, EMHN, URQ and CRCH, occurred above 25˚N (**Figure 6**). In the DS analysis, just eleven stations had a reduction in the dry spell, only TPB is significant, see **Figure 7**.

3.2. Geographic Analysis

Given the importance of orography in rainfall [70] and specifically for monsoonal processes like the North American Monsoon that drives the main fraction of precipitation in this watershed [37] [44], it can be expected that altitude can have a significant role in rainfall trends. [14] found evidence of divergent trends relative to oro-

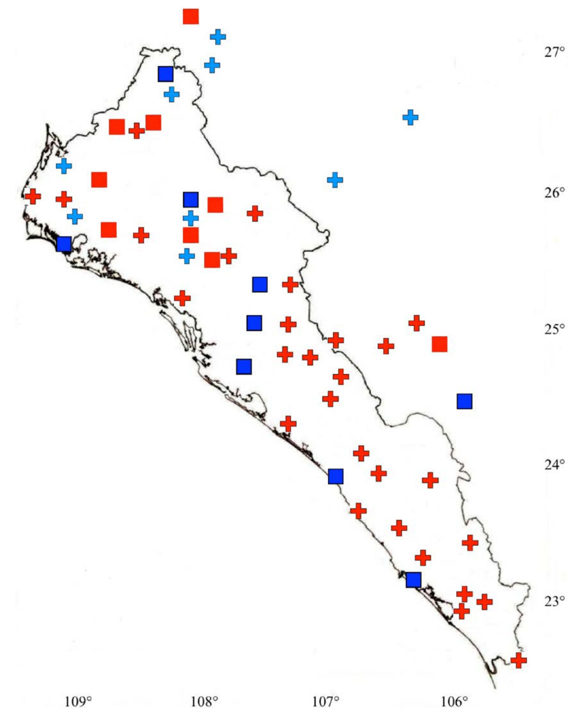

Figure 2. Interaction between PP-PCI trends, symbology: red crosses = decreasing PP – increasing PCI trends; red squares = decreasing PP – decreasing PCI trends; blue crosses = increasing PP – increasing PCI trends; blue squares = increasing PP – decreasing PCI trends. Trends were significant at $P < 0.05$.

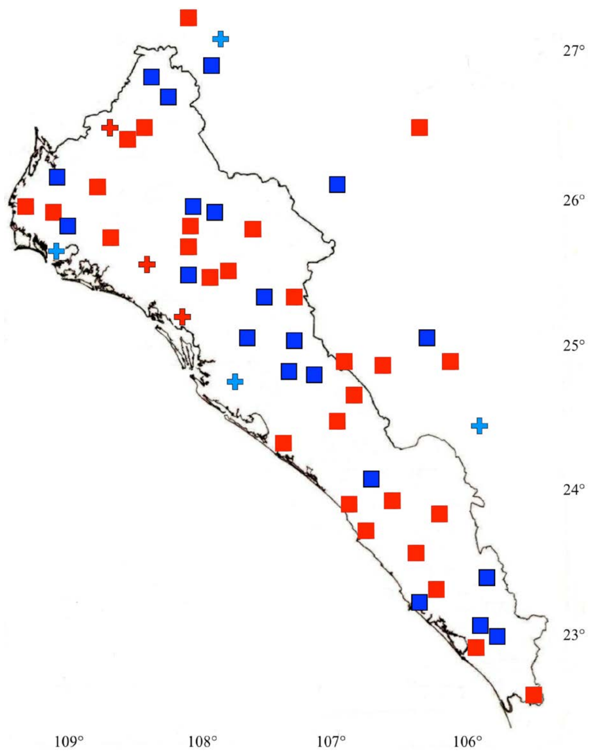

Figure 3. PPS trends, symbology: red crosses = decreasing significant trends, red squares = decreasing non-significant trends, blue crosses = increasing significant trends, blue squares = increasing non-significant trends. Trends were significant at $P < 0.05$.

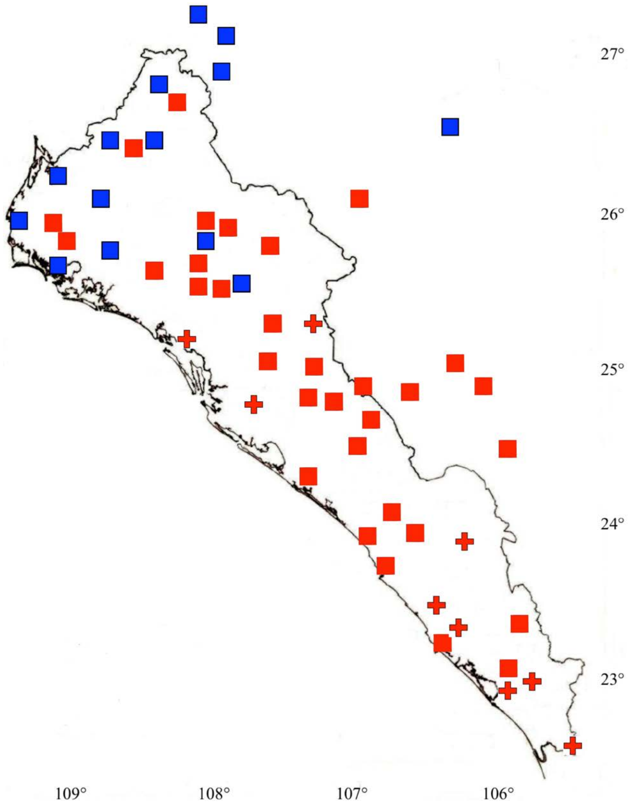

Figure 4. PPW trends, symbology: Same as in **Figure 3**. Trends were significant at $P < 0.05$.

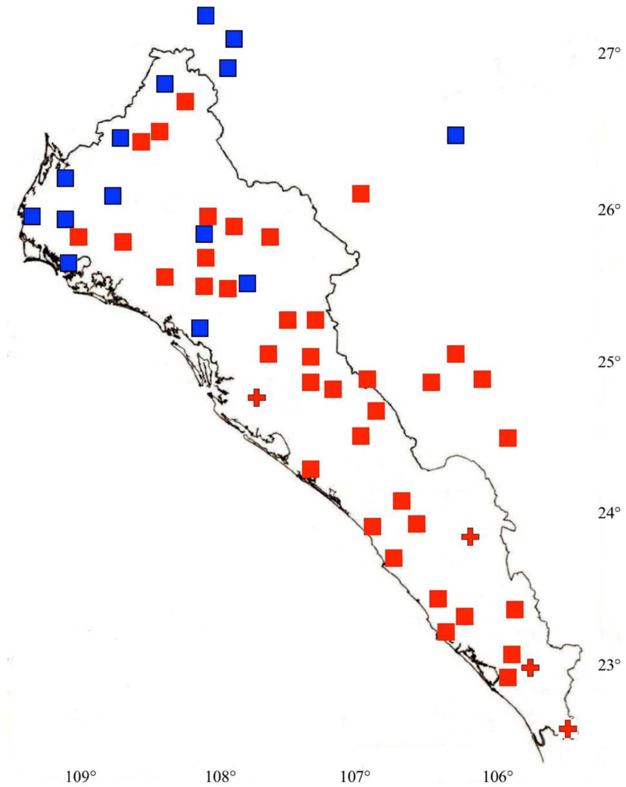

Figure 5. %PPW trends, symbology: same as in **Figure 3**. Trends were significant at $P < 0.05$.

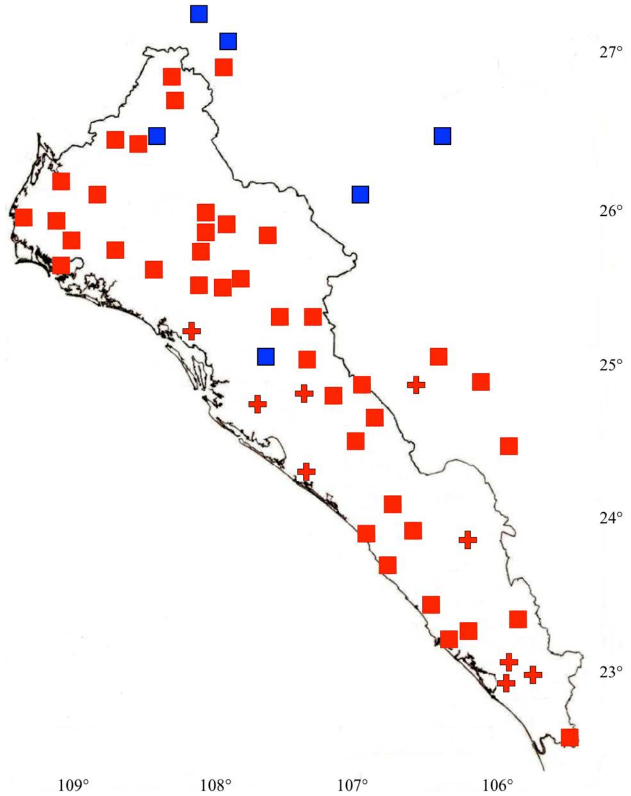

Figure 6. PP < 15 trends, symbology: same as in **Figure 3**. Trends were significant at $P < 0.05$.

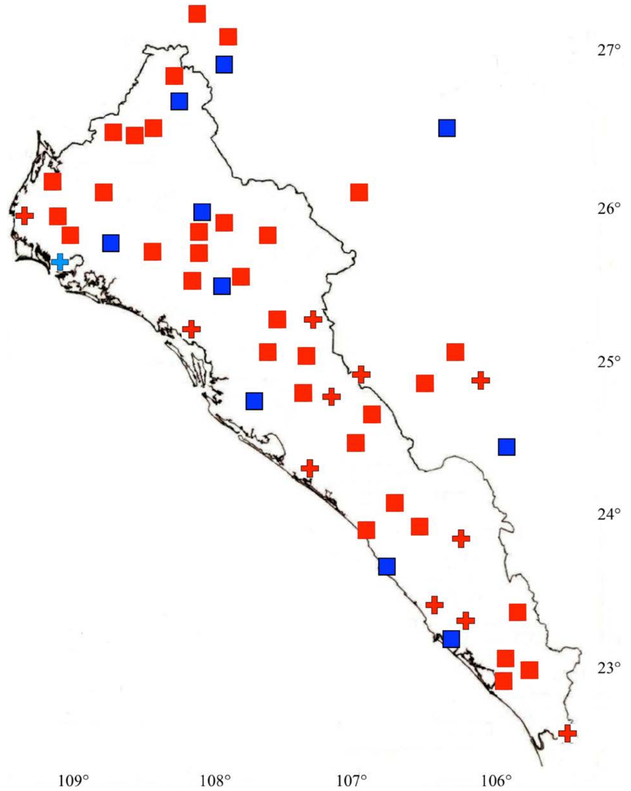

Figure 7. DS trends, symbology: same as in **Figure 3**. Trends were significant at $P < 0.05$.

graphic effects, with an increase in annual rainfall in elevated areas and an increase of drought length in lowland sites within a watershed, a similar result were found in this analysis, the increasing slope values of PP are largely associated to altitude. However, for the remaining variables estimated, latitude is a more conspicuous element in the geographic distribution of rainfall variables trends; longitude was the most relevant geographic element for PPS and DS slopes trends distribution. A potential explanation may be the larger magnitude of change in latitudinal way instead of altitudinal (**Table 2**).

An analysis estimating *I* Moran's index, shows that the trends of PCI, PPW, and %PPW developed significant clustered spatial distribution, the remaining variables trends tended to be dispersed (**Table 3**). The lack of spatial correlation for PP, PPS, PP < 15 and DS may be due to specific local conditions in each station, such as topography and seasonal irregularities linked to different levels of sensitivity to larger climate phenomena such as El Niño, its counterpart La Niña, strong winter cold fronts, among another events, that might cause the delay or anticipation in the start of the rainy season or strong winter rainfalls. There are stations within a homogeneous landscape and relatively short distance that present divergent trends such as AHM-LMCH and DMS-LCRZ for PP, GML-MCT and IXP-ACT for PPS amid other cases.

This result requires further research at a more fine-grained level of measurement.

After rotating the data from a PCA analysis**,** three major components are retained. The matrix component loadings are shown in **Table 4**. It can be clearly distinguished the relevance of PPS and PP on the first component, whilst PPW and %PPW have the same effect on the second component, which is outstanding, given the apparent scarce relevance in terms of quantity in the total yearly precipitation amount, but highlighting its importance in the whole regional rainfall pattern.

Even when in Sinaloa and within this watershed the physiographic regions are plainly defined mainly based on altitude, and these conditions play a significant role on climate conditions [46] [71]. For this analysis, the bi-dimensional scatterplot of *z*-standardized scores resulting from a PCA analysis (**Figure 5**) show an association pattern that clusters sites in response to trend similarity, clearly distant from its geographic and orographic position, sites evidently distant in spatial and physiographic terms showed a similar trend behavior such as NVT and LTRC. On the other extreme, sites such as EPLY and TPB that are very similar developed diametrically

Table 2. r^2 and standardized β coefficient values of multiple regression analysis with climate Sen's slope values as dependent variables and latitude, longitude and altitude as independent variables from weather stations in the North Pacific Watershed in México. Bold figures indicate significant values at $P < 0.05$.

Factor	PP	PCI	PPS	PPW	%PPW	PP < 15	DS
r^2	0.059	**0.190**	0.035	**0.153**	0.126	0.127	0.029
Latitude	0.049	−0.550	0.157	0.612	0.321	−0.471	−0.003
Longitude	−0.165	−0.162	0.180	0.264	−0.047	−0.230	0.165
Altitude	0.183	0.003	0.082	−0.227	−0.046	−0.052	−0.114

Table 3. Moran *I* index values of the slopes of rainfall variables from weather stations in the North Pacific Watershed. Bold figures indicate significant values a $P < 0.05$.

PP	PCI	PPS	PPW	%PPW	PP < 15	DS
−0.0108	**0.0321**	−0.0281	**0.0357**	**0.0738**	−0.0012	−0.0210

Table 4. Promax rotated structure matrix component loadings of slope values from weather stations in the North Pacific Watershed. Empty cells denote loadings with values below 0.300.

Component	PP	PCI	PPS	PPW	%PPW	PP < 15	DS
1	0.863	***	0.910	0.377	***	***	−0.686
2	0.643	−0.486	0.340	0.894	0.832	***	***
3	***	0.750	***	***	−0.364	0.867	0.362

opposite trends. **Figure 8** describes the association of *z*-standardized scores of each site, between the first two principal components that define 64% of the total variance.

3.3. Possible Effects of Primary Economic Activities

In Sinaloa, the largest economic activity is agriculture, which due to its geographic position and marked seasonality is highly dependent on water availability, temperature are strongly correlated with vegetation and soil. In order to increase the productivity, the first area to be broadly affected was the CP, where the thorn forest was cleared, in the late decade of the 50s and early 60s the rate of clearings increased with the construction of dams and irrigation channels mainly from mid to north Sinaloa. In the Sierra Foothills a more intense rate of vegetation removal took place in the late decade of the 60s and early 70s, clearing the tropical dry forest for temporal agricultural purposes, and an artisanal but increasing and generalized production of charcoal has been occurring since the decade of the 80s to the present days. In the Sierra Madre region, the main problem is logging, either illegal or purposely legal but without any kind of control. The sum of these processes in Sinaloa is reflected by the elevated deforestation rate: 11000 $ha \cdot y^{-1}$ which is one of the highest in México [72]. Recently, since the 80s decade, an even larger pressure on the CP region has occurred due to the construction of shrimp farms along the coast line, eliminating almost entirely the original vegetation cover of thorn forest and mangrove [73]. In the same fashion, in the SF and the SM regions, the establishments of open mining fields are destroying large areas of original vegetation.

Regarding agriculture, [74] reported an increasing demand of hydric need for crops due to climate change conditions, derived by the effect of rainfall decrease and increasing temperatures in evapotranspiration processes [75]. Specifically in northern Sinaloa, [76] analyzed the potential impacts in an irrigation district, finding that moving the planting season towards autumn-winter will be necessary to avoid the effects of increasing thermal and drying trends. So far, no studies have been made for temporal agriculture, outside irrigation fields, where the peasants depend solely on seasonal rainfall.

The increasing irregularities and shrinking amounts of rainfall in a large portion of the analyzed area, may place the ecosystem functions and water availability in a situation of growing concern for the determination of natural resource management. According to a report developed by [77] Sinaloa is a highly risk area in the context of climate change, due to the increase in drought episodes and rainfall intensity events, mainly associated with storms, which is mirrored by the results here presented. Environmental degradation has consequences in every biological field, including productive activities, necessarily linked to the environment and its resources

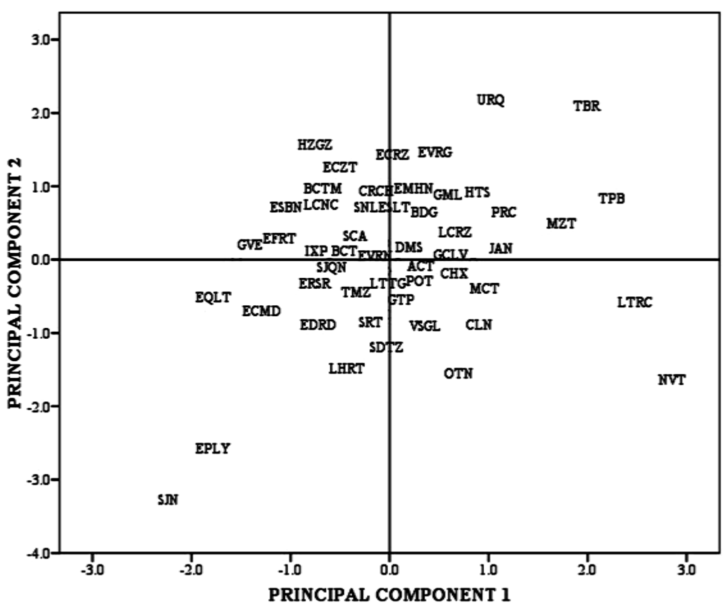

Figure 8. Scatter plot of *z*-standardized scores of the first to principal component analysis. See **Table 1** for abbreviations.

and consequently with social implications. Naturally, the ecosystems in northwest in Sinaloa and northwest México are seasonally productive, but in a fast-changing environment, subject to drying trends and global warming, biological responses and productive activities are increasingly exposed to growing severe conditions, imposing harder circumstances to achieve a minimum of regular responses and turning them almost impossible to reach. Given the high vulnerability of the ecosystems encompassing this region, besides a very poor water management in a naturally drought-prone situation is urgent to evaluate at a more detailed level the mechanisms governing the entire regional process of change, to create a theoretical background to propose and execute mitigation, conservation and restoration programs. Furthermore, by not recognizing or ignoring the mechanisms of this process and adding the poor natural resource management, the feedback created will only make things worse, creating a growing environmental problem with ultimately social unrest, since the most vulnerable people live in poverty and is the largest fraction of the population [78].

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References

[1] Allen, M.R. and Ingram, W.J. (2007) Constraints on Future Changes in Climate and Hydrological Cycle. *Nature*, **419**, 224-232. http://dx.doi.org/10.1038/nature01092

[2] Huntington, T.G. (2006) Evidence for Intensification of the Global Water Cycle: Review and Synthesis. *Journal of Hydrology*, **319**, 83-95. http://dx.doi.org/10.1016/j.jhydrol.2005.07.003

[3] Mariotti, A., Struglia, M.V., Zeng, N. and Lau, K.M. (2002) The Hydrological Cycle in the Mediterranean Region and Implications for the Water Budget of the Mediterranean Sea. *Journal of Climate*, **15**, 1674-1690. http://dx.doi.org/10.1175/1520-0442[2002)015<1674:THCITM>2.0.CO;2

[4] Mauguet, S.A. (2006) Intra-Top Multi-Decadal Terrestrial Precipitation Regimes at the End of the 20th Century. *Climate Change*, **78**, 317-340. http://dx.doi.org/10.1007/s10584-006-9129-z

[5] Hulme, M., Osborn, T.J. and Johns, T.C. (1998) Precipitation Sensitivity to Global Warming: Comparison of Observations with HADMCM2 Simulations. *Geophysical Research Letters*, **25**, 3379-3382. http://dx.doi.org/10.1029/98GL02562

[6] Lambert, F., Stott, P. and Allen, M. (2003) Detection and Attribution of Changes in Global Terrestrial Precipitation. *Geophysical Research Letters*, **5**, Article ID: 06140.

[7] Dore, M.H.I. (2005) Climate Change and Changes in Global Precipitation Patterns: What Do We Know. *Environmental International*, **31**, 1167-1181. http://dx.doi.org/10.1016/j.envint.2005.03.004

[8] Rodríguez-Puebla, C., Encinas, A.H., Nieto, S. and Garmendia, J. (1998) Spatial and Temporal Patterns of Annual Precipitation Variability over the Iberian Peninsula. *International Journal of Climatology*, **18**, 299-316. http://dx.doi.org/10.1002/[SICI)1097-0088[19980315)18:3<299::AID-JOC247>3.0.CO;2-L

[9] Gemmer, M., Becker, S. and Jiang, T. (2004) Observed Monthly Precipitation in China 1951-2002. *Theoretical and Applied Climatology*, **77**, 39-45. http://dx.doi.org/10.1007/s00704-003-0018-3

[10] Kayano, M.T. and Sansígolo, C. (2008) Internannual to Decadal Variations of Precipitation and Daily Maximum and Daily Minimum Temperatures in Southern Brazil. *Theoretical and Applied Climatology*, **97**, 81-90. http://dx.doi.org/10.1007/s00704-008-0050-4

[11] Dai, A., Fung, I.Y. and Genio, A.D. (1997) Surface Observed Global Land Precipitation Variations during 1900-1988. *Journal of Climate*, **10**, 2943-2962. http://dx.doi.org/10.1175/1520-0442(1997)010<2943:SOGLPV>2.0.CO;2

[12] New, T., Todd, M., Hulme, M. and Jones, P. (2001) Precipitation Measurement and Trends in the Twentieth Century. *International Journal of Climatology*, **21**, 1899-1922. http://dx.doi.org/10.1002/joc.680

[13] Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein-Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden, B. and Zhai, P. (2007) Observations: Surface and Atmospheric Climate Change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L., Eds., *Climate Change* 2007: *The Physical Science Basis*, *Contribution of Working Group I to the* 4*th Assessment Report of The Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, 238.

[14] Aldrian, E. and Djamil, Y.S. (2008) Spatio-Temporal Climate Change of Rainfall in East Java. *International Journal of Climatology*, **28**, 435-448. http://dx.doi.org/10.1002/joc.1543

[15] Patra, J.P., Mishra, A., Singh, R. and Raghuwanshi, N.S. (2012) Detecting Rainfall Trends in Twentieth Century (1871-2006) over Orissa State, India. *Climatic Change*, **111**, 801-807. http://dx.doi.org/10.1007/s10584-011-0215-5

[16] O'Brien, K. (1995) Deforestation and Climate Change in the Selva Lacandona of Chiapas, México: Some Preliminary Results. *Norwegian Journal of Geography*, **49**, 105-122.

[17] O'Brien, K.L. (1998) Tropical Deforestation and Climate Change: What Does the Record Reveal? *Professional Geographer*, **50**, 140-135. http://dx.doi.org/10.1111/0033-0124.00110

[18] González-Méndez, J., Navar-Cháidez, J. and González-Ontiveros, V. (2008) Análisis de tendencias de precipitación (1920-2004) en México. *Investigaciones Geográficas, Boletín del Instituto de Geografía UNAM*, **65**, 38-55.

[19] Woodward, F.I. and Williams, B.G. (1987) Climate and Plant Distribution at Global and Local Scales. *Vegetatio*, **69**, 189-197. http://dx.doi.org/10.1007/BF00038700

[20] Pauses, J.G. and Austin, M.K. (2001) Patterns of Plant Species Richness in Relation to Different Environments: An Appraisal. *Journal of Vegetation Science*, **12**, 153-166. http://dx.doi.org/10.2307/3236601

[21] Holbrook, N.M., Whitbeck, J.L. and Mooney, H.A. (1995) Drought Responses of Neotropical Dry Forests Trees. In: Bullock, S.H., Medina, E. and Mooney, H.A., Eds., *Seasonally Dry Tropical Forests*, Cambridge University Press, Cambridge, 243-276. http://dx.doi.org/10.1017/CBO9780511753398.010

[22] Williams, C.A. and Albertson, J.D. (2006) Dynamical Effects of the Statistical Structure of Annual Rainfall on Dryland Vegetation. *Global Change Biology*, **12**, 777-792. http://dx.doi.org/10.1111/j.1365-2486.2006.01111.x

[23] Chapin III, F.S. (2003) Effects of Plants Traits on Ecosystem and Regional Processes: A Conceptual Framework for Predicting the Consequences of Climate Change. *Annals of Botany*, **91**, 455-463. http://dx.doi.org/10.1093/aob/mcg041

[24] Medina, E. (1995) Diversity of Life Forms of Higher Plants in Neotropical Dry Forest. In: Bullock, S.H., Medina, E. and Mooney, H.A., Eds., *Seasonally Dry Tropical Forests*, Cambridge University Press, Cambridge, 221-242. http://dx.doi.org/10.1017/CBO9780511753398.009

[25] Parmesan, C. and Yohe, G. (2003) A Globally Coherent Fingerprint of Climate Change Impacts across Natural Systems. *Nature*, **421**, 37-42. http://dx.doi.org/10.1038/nature01286

[26] Parmesan, C. (2006) Ecological and Evolutionary Responses to Recent Climate Change. *Annual Review of Ecology, Evolution, and Systematics*, **37**, 637-699. http://dx.doi.org/10.1146/annurev.ecolsys.37.091305.110100

[27] Bradley, N.L., Leopold, A.C., Ross, J. and Huffaker, W. (1999) Phenological Changes Reflect Climate Change in Wisconsin. *Proceedings of the National Academy of Sciences of the United States of America*, **96**, 9701-9704. http://dx.doi.org/10.1073/pnas.96.17.9701

[28] Rennenberg, H., Loreto, F., Polle, A., Brilli, F., Fares, S., Beniwal, R.S. and Gessler, A. (2006) Physiological Responses of Forests Trees to Heat and Drought. *Plant Biology*, **8**, 556-571. http://dx.doi.org/10.1055/s-2006-924084

[29] Sherry, R.A., Zhou, X.H., Gu, S.L., Arnone, A., Schimel, D.S., Verburg, P.S., Wallace, L.L. and Luo, Y.Q. (2007) Divergence of Reproductive Phenology under Climate Warming. *Proceedings of the National Academy of Sciences of the United States of America*, **104**, 198-202. http://dx.doi.org/10.1073/pnas.0605642104

[30] Pitelka, L.F. and Plant Migration Workshop Group (1997) Plant Migration and Climate Change. *American Scientist*, **85**, 464-473.

[31] Sánz-Elorza, M., Dana, E.D., González, A. and Sobrino, E. (2003) Changes in the High-Mountain Vegetation of the Central Iberian Peninsula as a Probable Sign of Global Warming. *Annals of Botany*, **92**, 273-280. http://dx.doi.org/10.1093/aob/mcg130

[32] Bradshaw, W.E. and Holzapfel, C.M. (2001) Genetic Shift in Photoperiodic Response Correlated with Global Warming. *Proceedings of the National Academy of Sciences of the United States of America*, **98**, 14509-14511. http://dx.doi.org/10.1073/pnas.241391498

[33] van Dijk, H. and Hautekèete, N. (2007) Long Day Plants and the Response to Global Warming: Rapid Evolutionary Change in Day Length Sensitivity Is Possible in Wild Beet. *Journal of Evolutionary Biology*, **20**, 349-357. http://dx.doi.org/10.1111/j.1420-9101.2006.01192.x

[34] Swetnam, T.W. and Betancourt, J.L. (1998) Mesoscale Disturbance and Ecological Response to Decadal Climatic Variability in the American Southwest. *Journal of Climate*, **11**, 3128-3147. http://dx.doi.org/10.1175/1520-0442(1998)011<3128:MDAERT>2.0.CO;2

[35] Randall, D.A., Wood, R.A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R.J., Sumi, A. and Taylor, K.E. (2007) Climate Models and Their Evaluation. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquies, M., Averyt, K.B., Tignor, M. and Miller, H.M., Eds., *Climate Change* 2007: *The Physical Science Basis. Contribution of Working Group I to the* 4*th Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, 662.

[36] INEGI (2006) Anuario Estadístico de Los Estados Unidos Mexicanos. Instituto Nacional de Estadística, Geografía e Informática.

[37] Douglas, M.W., Maddox, R.A., Howard, K. and Reyes, S. (1993) The Mexican Monsoon. *Journal of Climate*, **6**, 1665-

1677. http://dx.doi.org/10.1175/1520-0442(1993)006<1665:TMM>2.0.CO;2

[38] Adams, D.K. and Comrie, A.C. (1997) The North American Monsoon. *Bulletin of the American Meteorological Society*, **78**, 2197-2213. http://dx.doi.org/10.1175/1520-0477(1997)078<2197:TNAM>2.0.CO;2

[39] Hu, Q. and Feng, S. (2006) Decadal Variation in the Southwest US Summer Monsoon Circulation and Rainfall in a Regional Model. *Journal of Climate*, **20**, 4702-4716. http://dx.doi.org/10.1175/JCLI4270.1

[40] Hu, Q. and Feng, S. (2002) Interannual Rainfall Variations in the North American Summer Monsoon Region: 1900-1998. *Journal of Climate*, **15**, 1189-1202. http://dx.doi.org/10.1175/1520-0442(2002)015<1189:IRVITN>2.0.CO;2

[41] Englehart, P.J. and Douglas, A.V. (2001) The Role of Eastern North Pacific Tropical Storms in the Rainfall Climatology of Western México. *International Journal of Climatology*, **21**, 1370-1357. http://dx.doi.org/10.1002/joc.637

[42] Caso, M.C., González-Abraham, C. and Ezcurra, E. (2007) Divergent Ecological Effects of Oceanographic Anomalies on Terrestrial Ecosystems of the Mexican Pacific Coasts. *Proceedings of the National Academy of Sciences of the United States of America*, **104**, 10530-10535. http://dx.doi.org/10.1073/pnas.0701862104

[43] García-Oliva, F., Ezcurra, E. and Galicia, L. (1991) Pattern of Rainfall Distribution in the Central Pacific Coast of México. *Geografiska Annaler*: *Series A*, *Physical Geography*, **73**, 179-186. http://dx.doi.org/10.2307/521023

[44] Stensrud, D.J., Gall, R.L., Mullen, S.L. and Howard, K.W. (1995) Model of Climatology of the Mexican Monsoon. *Journal of Climatology*, **8**, 1775-1794. http://dx.doi.org/10.1175/1520-0442(1995)008<1775:MCOTMM>2.0.CO;2

[45] Rowe, A.K., Rutledge, S.A., Lang, T.J., Ciesielski, P.E. and Saleeby, S.M. (2008) Elevation-Dependent Trends in Precipitation Observed during NAME. *Monthly Weather Review*, **136**, 4962-4979. http://dx.doi.org/10.1175/2008MWR2397.1

[46] Nesbitt, S.W., Gochis, D.J. and Lang, T.J. (2008) The Diurnal Cycle of Clouds and Precipitation along the Sierra Madre Occidental Observed during NAME-2004. Implications for Warm Season Precipitation Estimation in Complex Terrain. *Journal of Hydrometeorology*, **9**, 728-743. http://dx.doi.org/10.1175/2008JHM939.1

[47] Rzedowski, J. (2006) Vegetación de México. 1 era Edición Digital. CONABIO, México City.

[48] Búrquez, A., Martínez-Yrízar, A., Felger, R.S. and Yetman, D. (1999) Vegetation and Habitat Diversity at the Southern Edge of the Sonoran Desert. In: Robichaux, Ed., *Ecology of the Sonoran Desert Plants and Plant Communities*, University of Arizona Press, Tucson, 50.

[49] Arundel, S. (2005) Using Spatial Models to Establish Climatic Limiters of Plants Species' Distribution. *Ecological Modeling*, **182**, 159-181. http://dx.doi.org/10.1016/j.ecolmodel.2004.07.016

[50] Neilson, R.P., Pitelka, L.F., Solomon, A.M., Nathan, R., Midgley, G.F., Fragoso, J.M.V., Lischle, H. and Thompson, K. (2005) Forecasting Regional to Global Plant Migration in Response to Climate Change. *Bioscience*, **55**, 749-759. http://dx.doi.org/10.1641/0006-3568(2005)055[0749:FRTGPM]2.0.CO;2

[51] Breshears, D.D., Cobb, N.S., Rich, P.M., Price, K.P., Allen, C.D., Ballce, R.G., Romme, W.H., Kastens, J.H., Floyd, M.L., Belnap, J., Anderson, J.J., Meyers, O.B. and Meyer, C.W. (2005) Regional Vegetation Die-Off in Response to Global-Change-Type Drought. *Proceedings of the National Academy of Sciences*, **102**, 15144-15148. www.pnas.org/cgi/doi/10.1073/pnas0505734102

[52] Kelly, A.E. and Goulden, M.L. (2008) Rapid Shifts in Plant Distribution with Recent Climate Change. *Proceedings of the National Academy of Sciences of the United States of America*, **105**, 11823-11826. http://dx.doi.org/10.1073/pnas.0802891105

[53] Dirkmeyer, P.A. and Shukla, J. (1994) Albedo as a Modulator of Climate Response to Tropical Deforestation. *Journal of Geophysical Research*, **99**, 863-877.

[54] Laurence, W.F. and Williamson, B.G. (2001) Positive Feedbacks among Forest Fragmentation, Drought and Climate Change in the Amazon. *Conservation Biology*, **15**, 1529-1535. http://dx.doi.org/10.1046/j.1523-1739.2001.01093.x

[55] Strengers, B.S., Müller, C., Schaeffer, M., Haarsma, R.J., Severijns, C., Gerten, D., Schapoff, S., van den Houdt, R. and Oostenrijk, R. (2010) Assessing 20th Century Climate-Vegetation Feedback of Land-Use Change and Natural Vegetation Dynamics in a Fully Coupled Climate Model. *International Journal of Climatology*, **30**, 2055-2065. http://dx.doi.org/10.1002/joc.2132

[56] Zheng, X. and Eltahir, E.A.B. (1997) The Response to Deforestation and Desertification in a Model of West African Monsoons. *Geophysical Research Letters*, **24**, 155-158. http://dx.doi.org/10.1029/96GL03925

[57] Sen, O.L., Wang, Y. and Wang, B. (2004) Impact of Indochina Deforestation on the East Asian Summer Monsoon. *Journal of Climate*, **17**, 1366-1380. http://dx.doi.org/10.1175/1520-0442(2004)017<1366:IOIDOT>2.0.CO;2

[58] Villers-Ruiz, L. and Trejo-Vázquez, I. (1997) Assessment of the Vulnerability of Forest Ecosystems to Climate Change in México. *Climate Research*, **9**, 87-93. http://dx.doi.org/10.3354/cr009087

[59] Oliver, J.E. (1980) Monthly Precipitation Distribution: A Comparative Index. *The Professional Geographer*, **32**, 300-309. http://dx.doi.org/10.1111/j.0033-0124.1980.00300.x

[60] Türkeş, M., Sümer, U.M. and Kiliç, G. (1996) Observed Changes in Maximum and Minimum Temperatures in Turkey. *International Journal of Climatology*, **16**, 463-477.

[61] Kadioğlu, M., Şen, Z. and Gültekin, L. (2001) Variation and Trends in Turkish Seasonal Heating and Cooling Degree-Days. *Climatic Change*, **49**, 209-233. http://dx.doi.org/10.1023/A:1010637209766

[62] Gemmer, M., Becker, S. and Jiang, T. (2004) Observed Monthly Precipitation in China, 1951-2002. *Theoretical and Applied Climatology*, **77**, 39-45. http://dx.doi.org/10.1007/s00704-003-0018-3

[63] Modarres, R. and da Silva, V.R. (2007) Rainfall Trends in Arid and Semi-Arid Regions of Iran. *Journal of Arid Environments*, **70**, 344-355. http://dx.doi.org/10.1016/j.jaridenv.2006.12.024

[64] Bae, D.H., Jung, I.W. and Chang, H. (2008) Long-Term Trend of Precipitation and Runoff in Korean River Basins. *Hydrological Processes*, **22**, 2644-2656. http://dx.doi.org/10.1002/hyp.6861

[65] De Luis, M., Raventós, J., González-Hidalgo, J.C., Sánchez, J.R. and Cortina, J. (2000) Spatial Analysis of Rainfall Trends in the Region of Valencia (East Spain). *Journal of International Climatology*, **20**, 1451-1469.

[66] Murugan, M., Mukund, V., Ramesh, R., Hiremath, M.B., Josephrajkumar A. and Shetty, P.K. (2008) Centennial Rainfall Variation in Semi-Arid and Tropical Humid Environments in the Cardamon Hill Slopes, Southern Western Ghats, India. *Caspian Journal of Environmental Sciences*, **6**, 31-39.

[67] Groisman, P.Y., Karl, T.R., Easterling, D.R., Knight, R.W., Jamason, P.F., Hennessy, K.J., Suppiah, R., Page, C.M., Wibig, J., Fortuniak, K., Razuvaev, V.N., Douglas, A., Forland, E. and Zhai, P.M. (1999) Changes in the Probability of Heavy Precipitation: Important Indicators of Climatic Change. *Climatic Change*, **42**, 243-283. http://dx.doi.org/10.1023/A:1005432803188

[68] Brunetti, M., Buffoni, L., Maugeri, M. and Nanni, T. (2000) Precipitation Intensity Trends in Northern Italy. *International Journal of Climatology*, **20**, 1017-1031.

[69] Brunetti, M., Maugeri, M. and Nanni, T. (2001) Changes in Total Precipitation, Rainy Days and Extreme Events in Northeastern Italy. *Journal of International Climatology*, **21**, 861-871. http://dx.doi.org/10.1002/joc.660

[70] Houze Jr., R.A. (2012) Orographic Effects on Precipitation Clouds. *Reviews of Geophysics*, **50**, Published Online. http://dx.doi.org/10.1029/2011RG000365

[71] Berbery, E.H. (2001) Mesoscale Moisture Analysis of the North American Monsoon. *Journal of Climate*, **14**, 121-137. http://dx.doi.org/10.1175/1520-0442(2001)013<0121:MMAOTN>2.0.CO;2

[72] Céspedes-Flores, S.E. and Moreno-Sánchez, E. (2010) Estimación de la pérdida del recurso forestal y su relación con la reforestación en las entidades federativas de México. *Investigación Ambiental*, **2**, 5-13.

[73] Ruiz-Luna, A. and Berlanga-Robles, C.A. (2003) Land Use, Land Cover Changes and Coastal Lagoon Surface Reduction Associated with Urban Growth in Northwest México. *Landscape Ecology*, **18**, 159-171. http://dx.doi.org/10.1023/A:1024461215456

[74] Rodríguez, J.A., Weatherhead, E.K., Knox, W. and Camacho, E. (2007) Climate Change Impacts on Irrigation Water Requirements in the Guadalquivir River Basin in Spain. *Regional Environmental Change*, **7**, 149-159. http://dx.doi.org/10.1007/s10113-007-0035-3

[75] Allen, R.G., Gichuki, F.N. and Resenzweig, C. (1991) CO_2-Induced Climatic Changes and Irrigation-Water Requirements. *Journal of Water Resources Planning and Management*, **117**, 157-178. http://dx.doi.org/10.1061/(ASCE)0733-9496(1991)117:2(157)

[76] Ojeda-Bustamante, Sifuentes-Ibarra, E., Íñiguez-Covarrubias, M. and Montero-Martínez, M.J. (2011) Climate Change Impact on Crop Development and Water Requirements. *Agrociencia*, **45**, 1-11.

[77] CENAPRED (2009) Atlas Nacional de Riesgos. Centro Nacional para la Prevención de Desastres.

[78] O'Brien, K.L. and Leichenko, R.M. (2000) Double Exposure: Assessing the Impact of Climate Change within the Context of Economic Globalization. *Global Environmental Change*, **10**, 221-232. http://dx.doi.org/10.1016/S0959-3780(00)00021-2